

# A sterile neutrino search with the MINOS experiment

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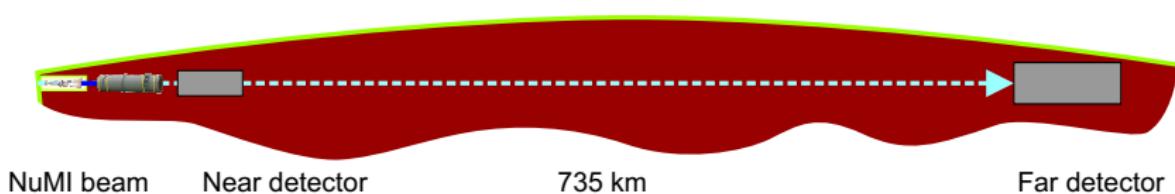
University of Oxford

May 25, 2010

# Introduction

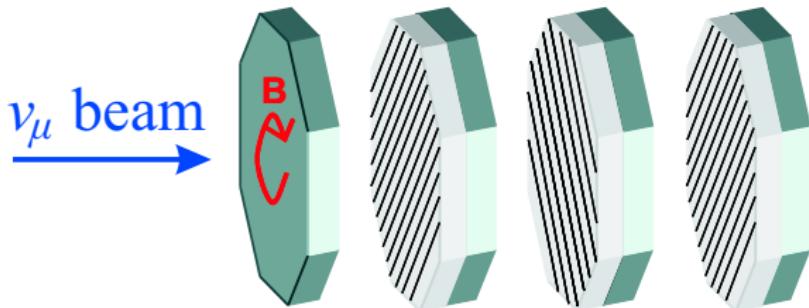
- ▶ The MINOS experiment
- ▶ Sterile  $\nu$
- ▶ NC analysis
  - ▶ Predicting the far detector spectrum
  - ▶ Reducing the normalization systematic
  - ▶ (Old) results

# MINOS experiment overview



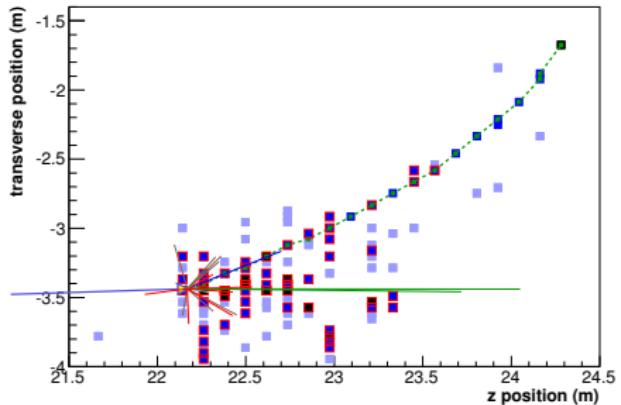
- ▶ Two-detector long-baseline  $\nu$  oscillation experiment
- ▶ Detectors as similar as possible: systematics cancellation

# The MINOS detectors

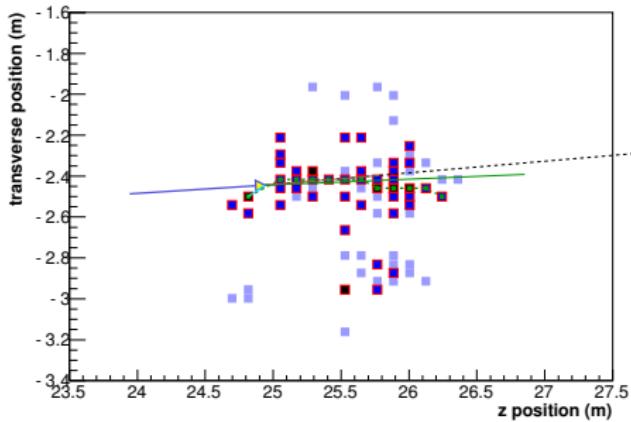


- ▶ Magnetized steel/scintillator sampling calorimeters
- ▶ Scintillator strips  $4.1\text{ cm} \times 1\text{ cm}$
- ▶ WLS fibre readout to multi-anode PMTs
- ▶ Near: 1 kt. Far: 5 kt

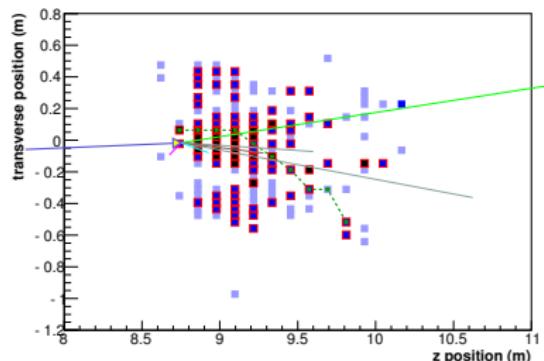
# Neutrino events in MINOS



CC  $\nu_\mu$



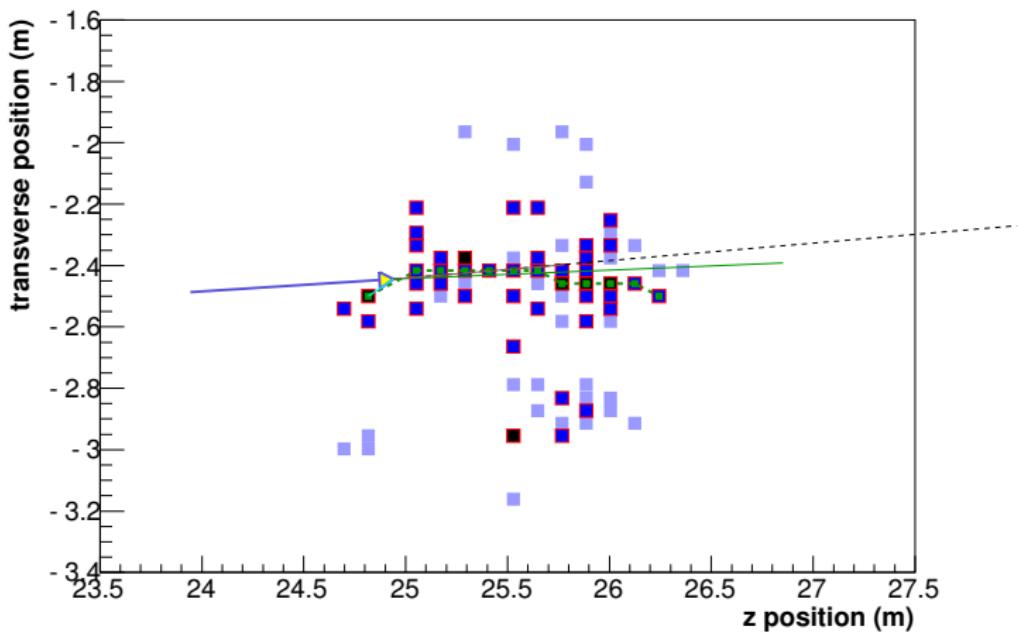
NC  $\nu_x$



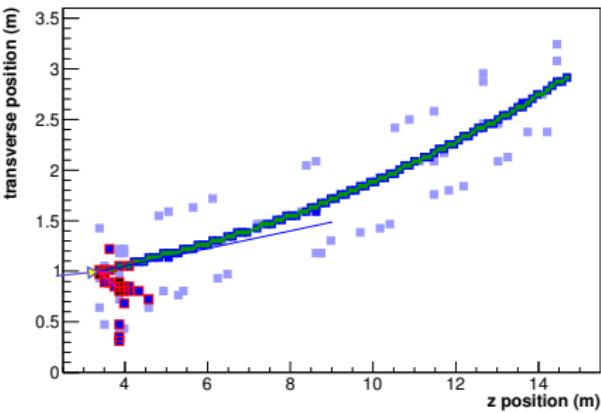
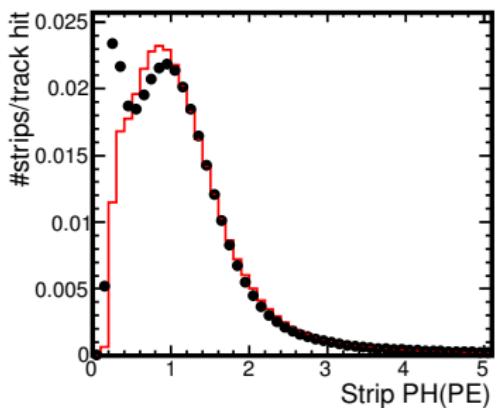
CC  $\nu_e$

# MINOS event reconstruction

- ▶ Aims:
  - ▶ Identify muon tracks
  - ▶ Accurately measure hadronic shower energy
- ▶ Non- $\mu$  ( $\pi^\pm/p/\text{fake}$ ) tracks in showers
- ▶ Low pulse-height hits excluded



## Low pulse height hits



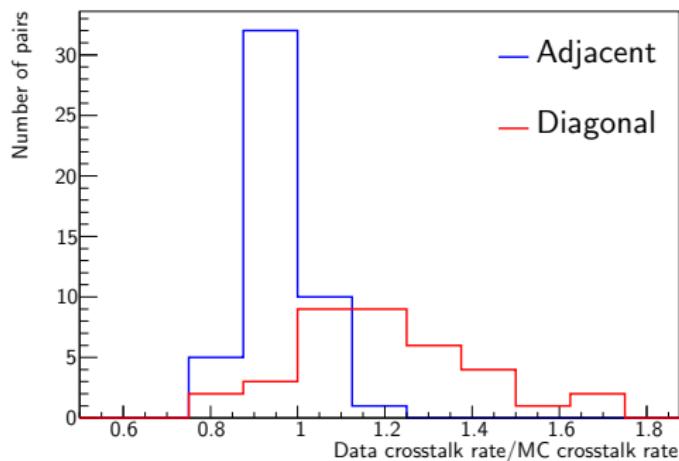
- ▶ Data/MC agreement at low PH bad
  - ▶ Detector effects: crosstalk, afterpulsing, fibre noise
- ▶ Neighbouring pixels  $\Leftrightarrow$  strips separated by  $\sim 0.5$  m
  - ▶ PMT crosstalk forms 'halo' around track

# Crosstalk measurements *in situ*

- ▶ Use clean tracks from cosmic-ray muons
- ▶ Consider hits in PMT pixel space
- ▶ Identify physics and crosstalk hits
- ▶ Compare data/MC crosstalk rates

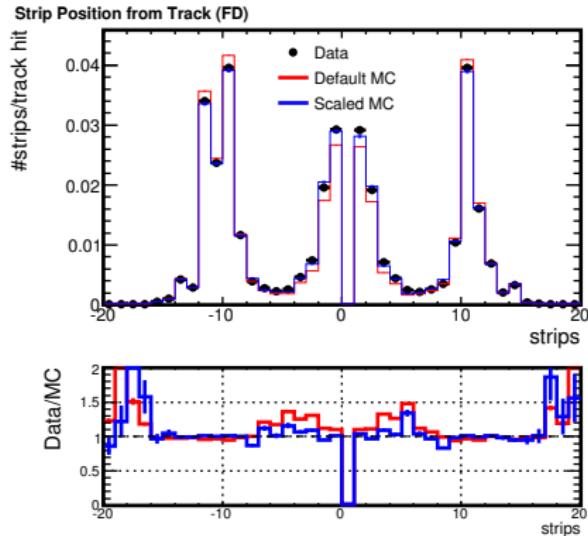
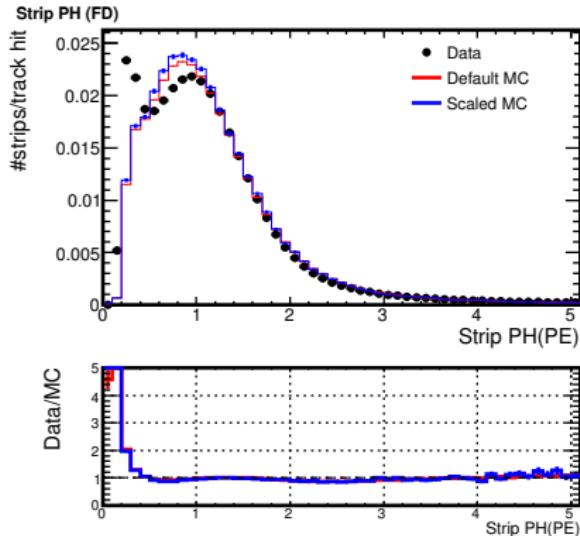
Pixel 0	Pixel 1	Pixel 2	Pixel 3
Pixel 4	Pixel 5	Pixel 6	Pixel 7
Pixel 8	Pixel 9	Pixel 10	Pixel 11
Pixel 12	Pixel 13	Pixel 14	Pixel 15

FD PMT with read out strips



# Tuned crosstalk

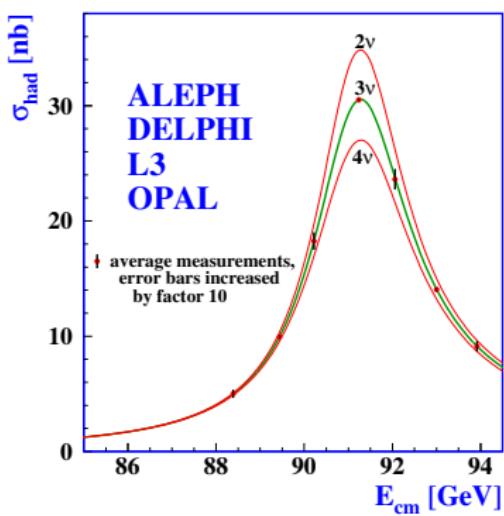
- ▶ Crosscheck for more thorough measurements from  $\nu_e$  group
  - ⇒ Tuned MC crosstalk near/far



- ▶ Improvement in rate, not spectrum
- ▶ Discard hits  $< 2 \text{ pe}$  from shower reco

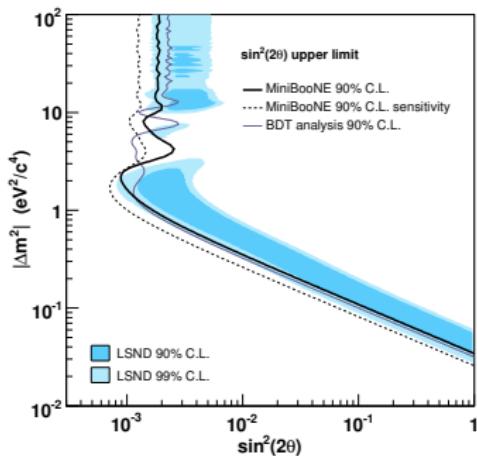
# Sterile neutrinos

- $Z$  peak  $\Rightarrow$  3  $\nu$  species:



- Motivation:

- HEP: LSND  $\nu_\mu \rightarrow \nu_e$  at  $\mathcal{O}(1 \text{ eV}^2)$ :

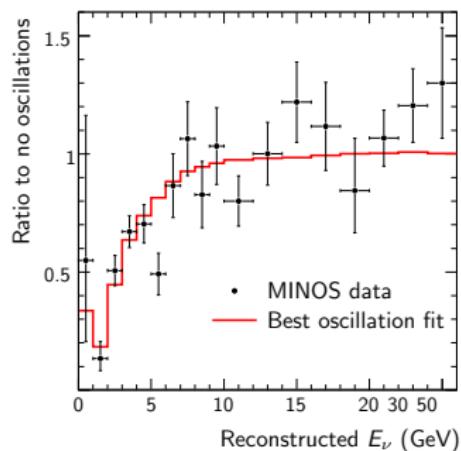


- Any other light  $\nu$ : *sterile*.
- No SM interactions

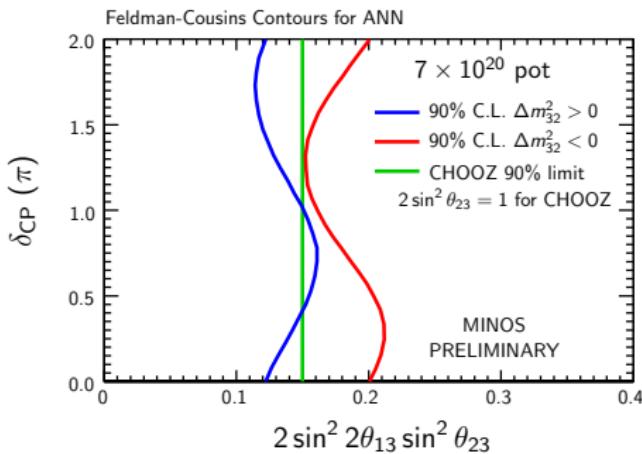
- Astro: Energy transport in supernovae

# Steriles in the atmospheric sector

- ▶ SuperK, MINOS:  $\nu_\mu$  disappearance



- ▶  $\nu_\mu \rightarrow \nu_e$  not observed



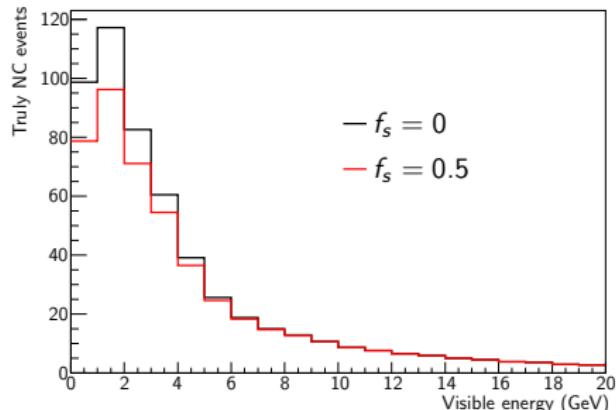
- ▶ Expect  $\nu_\mu \rightarrow \nu_\tau$
- ▶  $\nu_\mu \rightarrow \nu_s$  ?
- ▶ SuperK favours pure  $\nu_\mu \rightarrow \nu_\tau$  vs  $\nu_\mu \rightarrow \nu_s$  (99% C.L.)

# Sterile neutrinos in MINOS

- ▶  $\nu_\mu \rightarrow \nu_{e,\mu,\tau}$ : NC rate unchanged
  - ▶ but  $\nu_\mu \leftrightarrow \nu_s \Rightarrow$  NC deficit
- ▶ Parametrize using  $f_s$ :

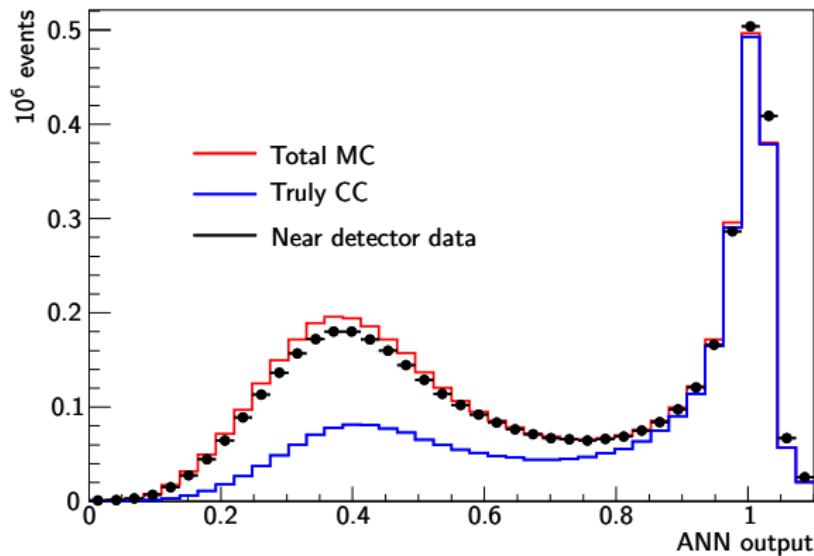
$$P(\nu_\mu \rightarrow \nu_s) = f_s \sin^2 2\theta_{23} \sin^2 \left( 1.27 \Delta m^2 \frac{L}{E} \right)$$

- ▶ Eg for  $f_s = 0.5$ , FD truly NC spectrum:



## Separating NC and CC events

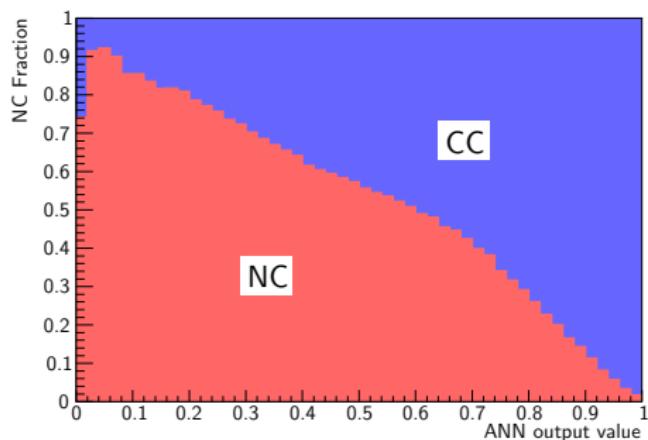
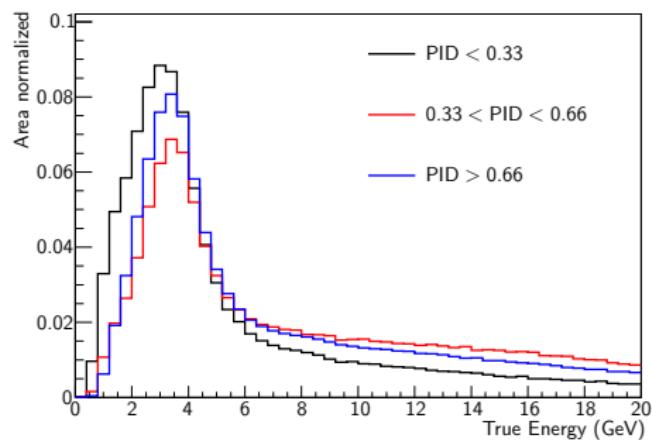
- ▶ ANN developed at Oxford
- ▶ Preselection:  $N_{\text{plane}} > 40$  CC;  $N_{\text{track}} = 0$  NC
- ▶ Seven input variables, feedforward network with one hidden layer



- ▶ NC selection:  $\varepsilon = 0.89$ ,  $p = 0.65$  possible

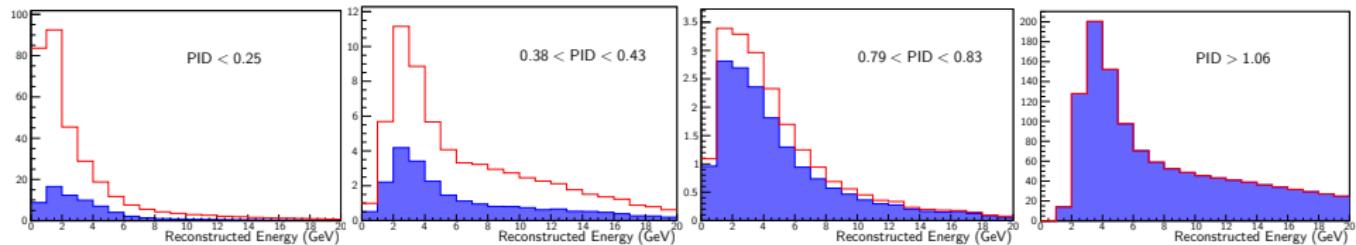
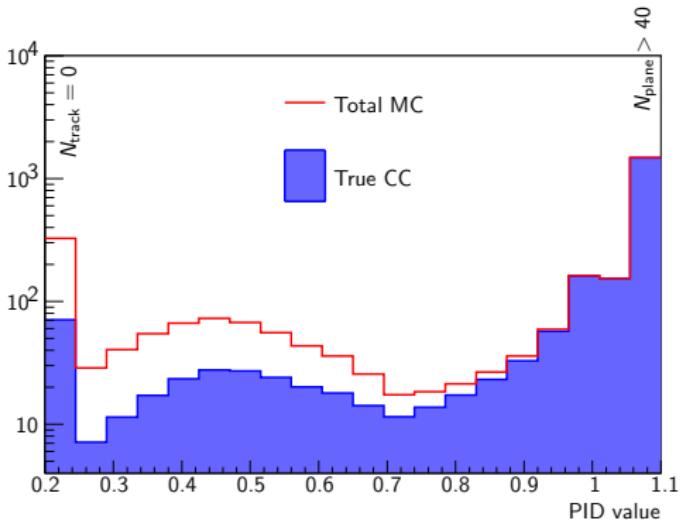
# Improving sensitivity

- True  $E_\nu$ , NC/CC ratio depend on PID



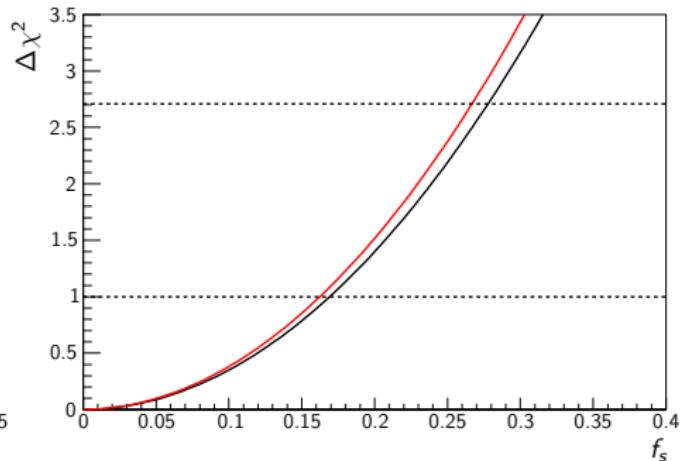
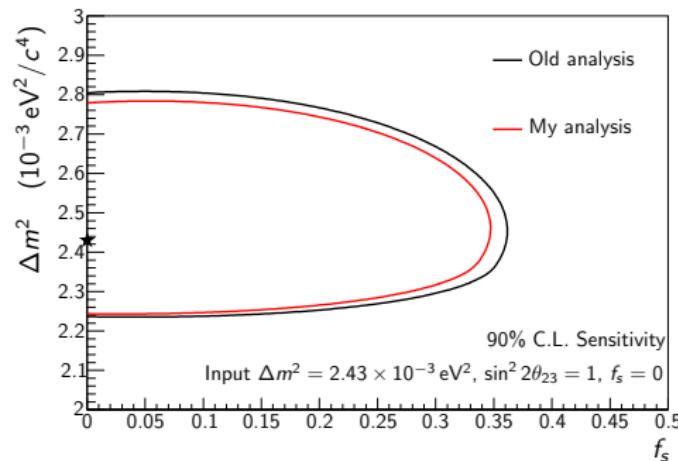
- Fit multiple spectra in PID ranges

# Energy spectra



FD unoscillated

## Sensitivity to sterile $\nu$



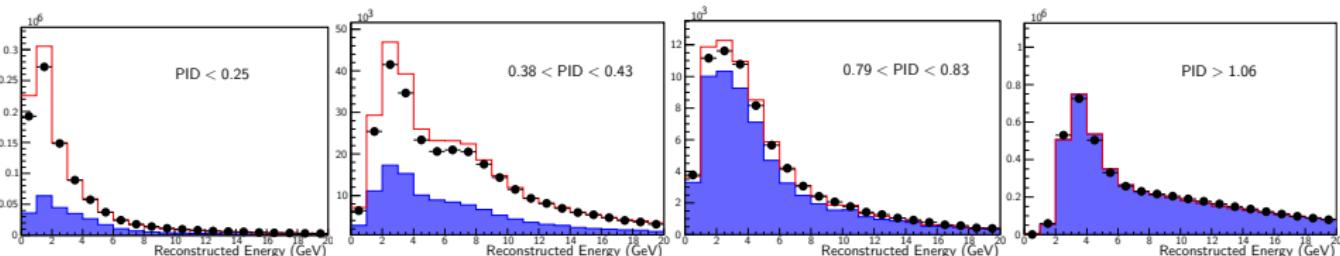
- ▶ Improved statistical sensitivity
- ▶  $f_s < 0.26$  (90% C.L.)

# Predicting the FD NC spectrum

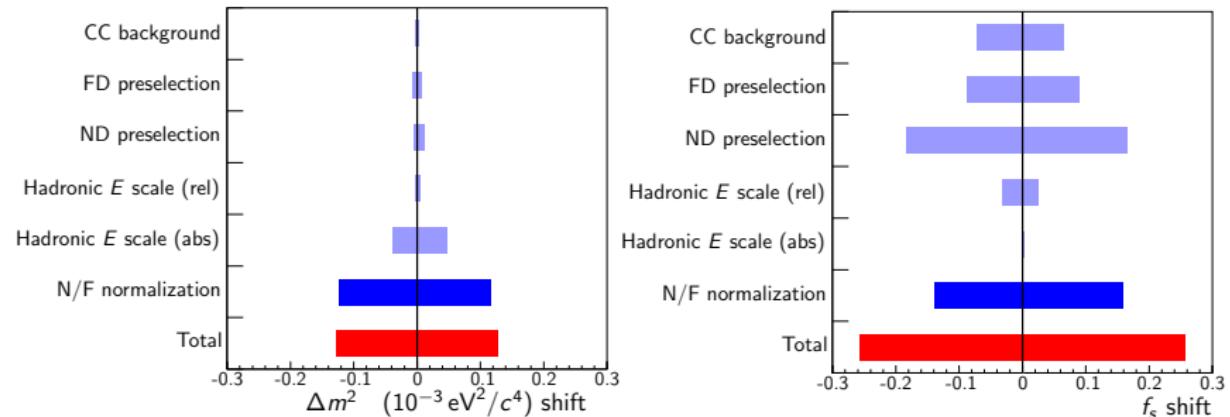
- ▶ Input from ND reduces systematics
- ▶ Predicted FD spectrum in each bin in each spectrum:

$$F_{\text{pred}} = \frac{F_{\text{MC}}}{N_{\text{MC}}} N_{\text{data}} \equiv \frac{N_{\text{data}}}{N_{\text{MC}}} F_{\text{MC}}$$

- ▶ Account for flux differences, cross sections



# Systematic uncertainties



- ▶ N/F normalization systematic significant
  - ▶ From near/far data/MC efficiency differences

$$R = \frac{\epsilon_{\text{near}}^{\text{data}} / \epsilon_{\text{near}}^{\text{MC}}}{\epsilon_{\text{far}}^{\text{data}} / \epsilon_{\text{far}}^{\text{MC}}}$$

## Contributions to N/F normalization uncertainty

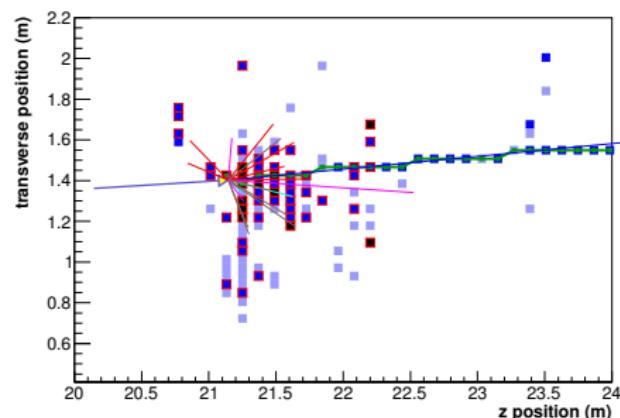
- ▶ Previous analysis:

Systematic	Contribution to relative uncertainty (%)
Steel thickness	0.2
Scintillator thickness	0.2
FD live time	1.0
ND fiducial bias	2.1
N/F reconstruction	3.0

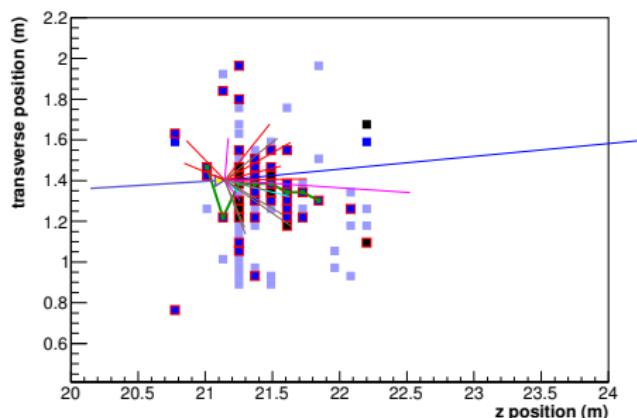
- ▶ FD live time, ND fiducial bias reduced for this analysis
- ▶ Reconstruction uncertainty largest

# Muon-removed charged current (MRCC) events

- ▶ Technique from MINOS  $\nu_e$  analysis
- ▶ CC  $\nu_\mu$  without track  $\approx$  NC event
- ▶ Remove track hits for data/MC pseudo-NC samples



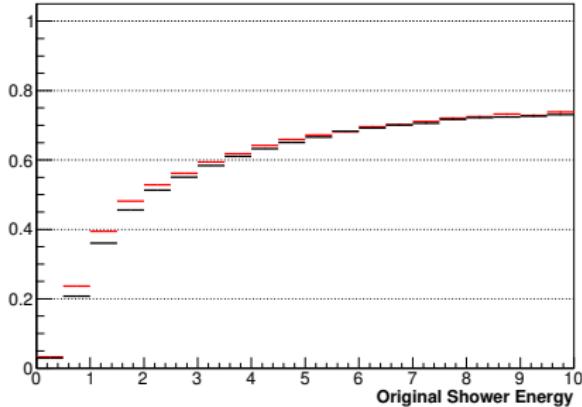
Before muon removal



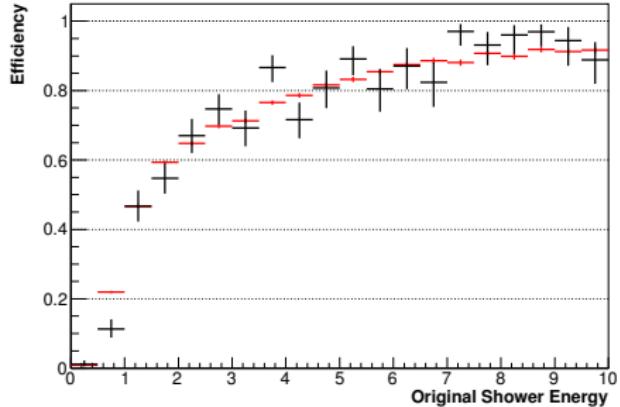
After muon removal

# Results from MRCC

Near Efficiencies



Far Efficiencies



- ▶ Reasonable data/MC agreement
- ▶ (Low in ND because of fiducial requirement)

$$R = 1.02$$

## Contributions to N/F normalization uncertainty: New

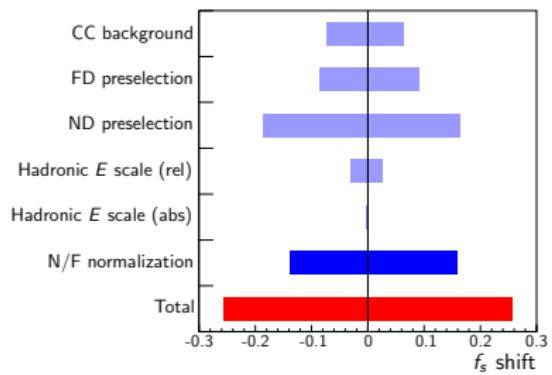
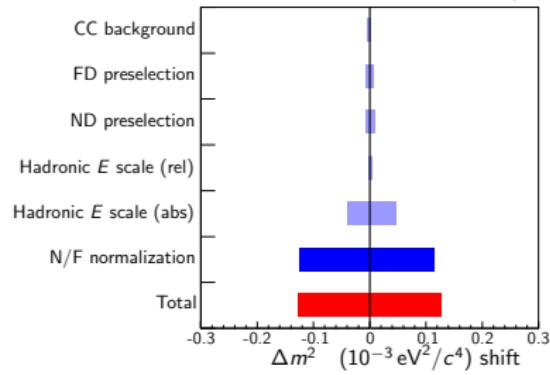
- ▶ This analysis:

Systematic	Contribution (%)	
	Old	New
Steel thickness	0.2	0.2
Scintillator thickness	0.2	0.2
FD live time	1.0	0.32
ND fiducial bias	2.1	0.7
N/F reconstruction	3.0	2.0
Total	4.0	2.2

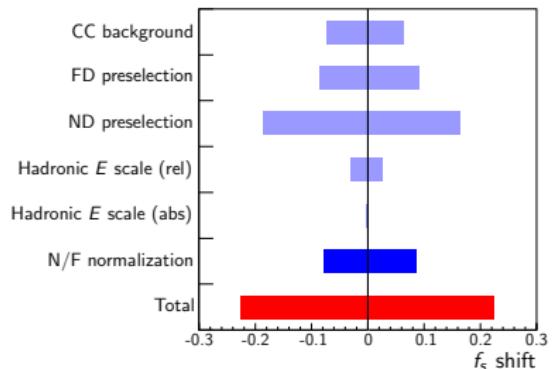
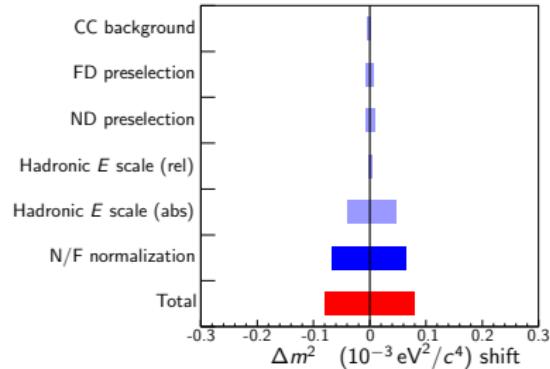
- ▶ Significant reduction in major systematic

# Systematic uncertainties: Old vs New

## Old N/F normalization

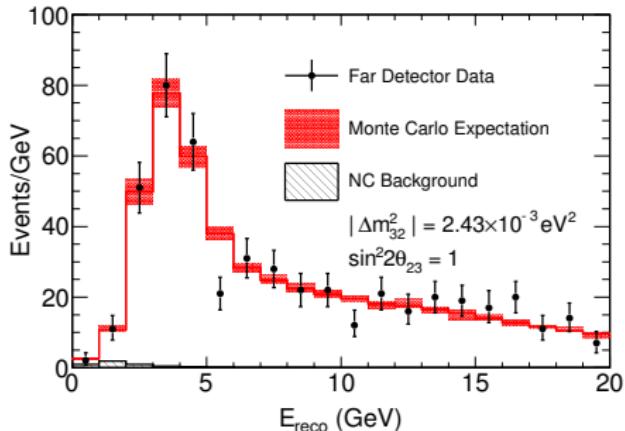
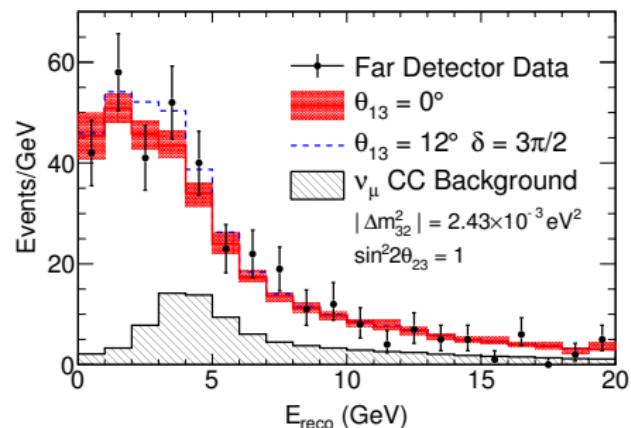


## New N/F normalization



# (Old) result

- ▶ Latest dataset blind. Old results:



- ▶ Consistent with 3-flavour model
- ▶  $f_s^* < 0.51$  (90% C.L.)
- ▶ Dataset doubled since

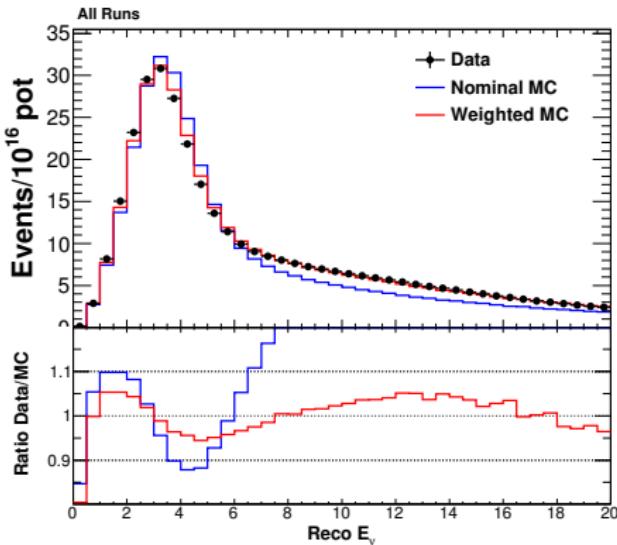
## Conclusions

- ▶ MINOS constrains  $\nu_\mu \rightarrow \nu_s$  via NC
- ▶ Improved sensitivity with my analysis
- ▶ Reduced major systematic error
- ▶ New results soon!

# Backup slides

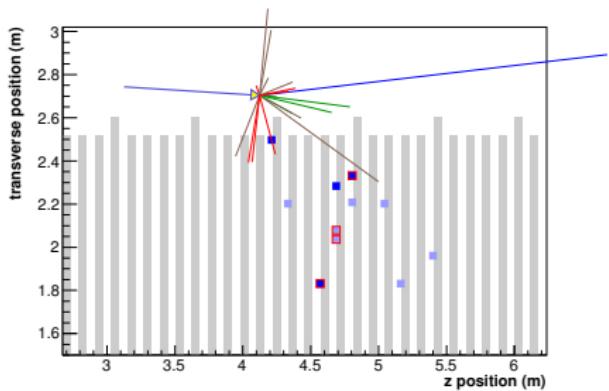
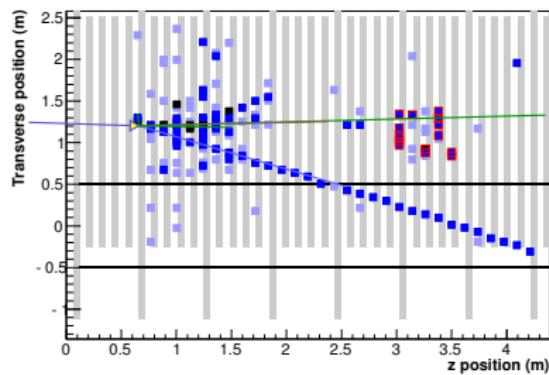
## Beam flux tuning

- ▶ Hadron production poorly modelled
- ▶ Use ND data to constrain
- ▶ Reweight events based on parent  $p_T$ ,  $p_z$

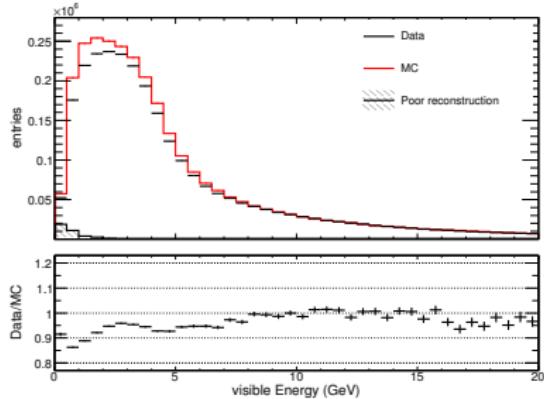
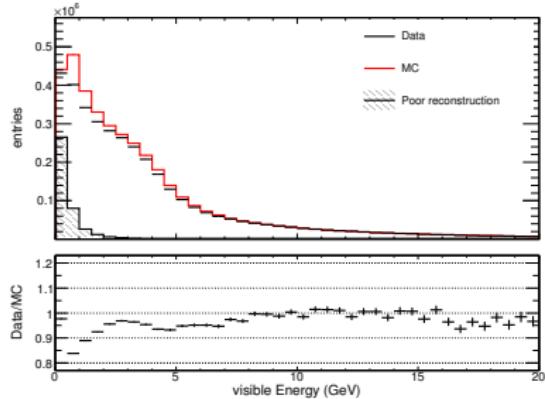
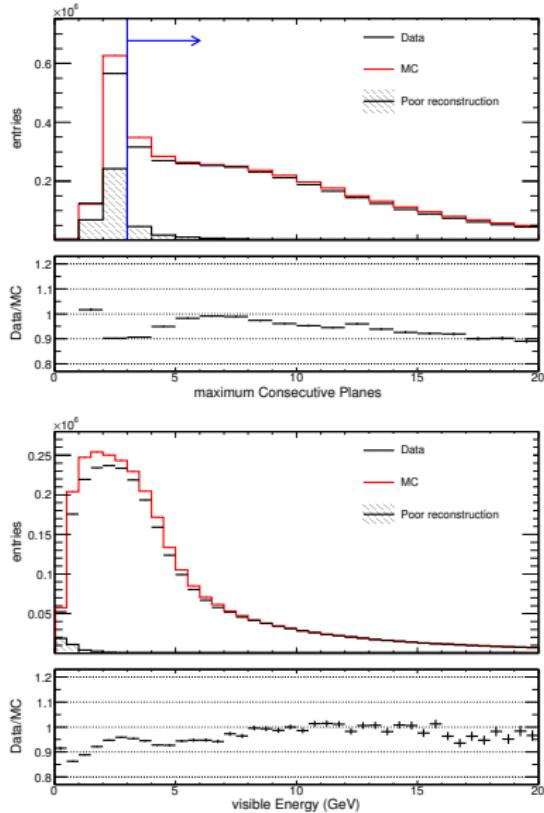
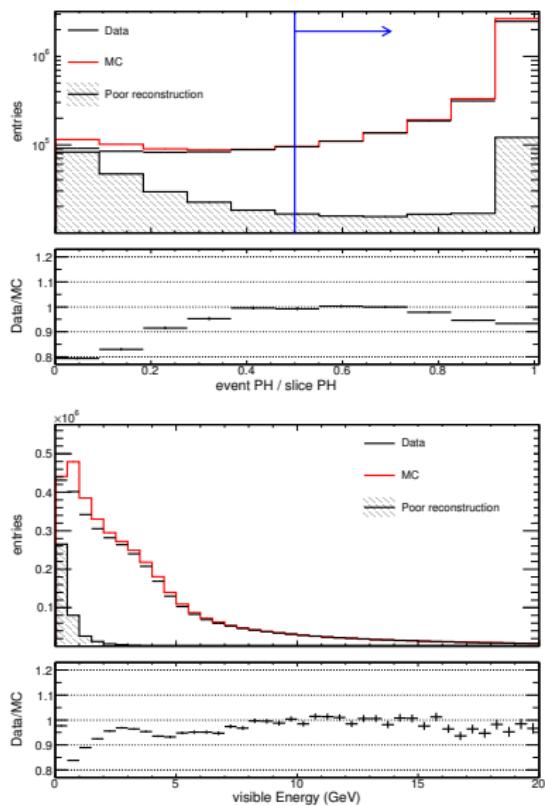


# Obtaining a reliable NC sample

- ▶ Fiducial: away from detector edges
- ▶ Poorly reconstructed events often NC-like:



# Reliable sample: ND cleaning



## Reliable sample: FD cleaning

- ▶ NC-like backgrounds:
  - ▶ High noise rate: noise events
  - ▶ Steep cosmic  $\mu$  in spill
  - ▶ Light injection in spill
- ▶ Cut on PH, event topology

# Constraining N/F with MRCC

- ▶ Aim:

$$R = \frac{\epsilon_{\text{near}}^{\text{data}} / \epsilon_{\text{near}}^{\text{MC}}}{\epsilon_{\text{far}}^{\text{data}} / \epsilon_{\text{far}}^{\text{MC}}}$$

- ▶ For data/MC, near/far:
  1. Take good CC  $\nu_\mu$  events
  2. Remove track, re-reconstruct
  3. Count fraction remaining  $\epsilon$

## Better MRCC estimate

- ▶ Issues:
  - ▶ Actual NC spectrum  $\neq$  MRCC spectrum ( $y$  dist)
  - ▶ Oscillations at far detector
- ▶ So: calculate  $\epsilon_i$  in energy bins
- ▶ Average weighted by NC spectrum in bin,  $n_i$ :

$$E = \frac{\sum_i \epsilon_i n_i}{\sum_i n_i}$$

- ▶ Use

$$R' = \frac{E_{\text{near}}^{\text{data}}/E_{\text{near}}^{\text{MC}}}{E_{\text{far}}^{\text{data}}/E_{\text{far}}^{\text{MC}}}$$

## Alternative models

- ▶  $\nu$  decay also gives NC deficit